

Diffuse Gamma-Ray Emission from Large Scale Structures

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Abstract. For more than a decade now the complete origin of the diffuse gamma-ray emission background (EGRB) has been unknown. Major components like unresolved star-forming galaxies (making $\lesssim 50\%$ of the EGRB) and blazars ($\lesssim 23\%$) have failed to explain the entire background observed by *Fermi*. Another, though subdominant, contribution is expected to come from the process of large-scale structure formation. The growth of structures is accompanied by accretion and merger shocks, which would, with at least some magnetic field present, give rise to a population of structure-formation cosmic rays (SFCR). Any cosmic-ray population results also in gamma-ray emission at some level due to interaction of cosmic-ray protons with ambient hydrogen, where gamma rays come from the decay of neutral pions created in this interaction. Though expected, this cosmic-ray population is still hypothetical and only very weak limits have been placed to their contribution to the EGRB. The most promising insight into SFCRs was expected to come from *Fermi*-LAT observations of clusters of galaxies, however only upper limits and no detection have been placed. Thus, the SFCR contribution to the EGRB is even smaller than previously expected, but still unknown. Here we build a model of gamma-ray emission from large-scale accretion shocks implementing a source evolution calibrated with the *Fermi*-LAT cluster observation limits. Together with contribution of normal star-forming galaxies, our modeled SFCR gamma-ray emission, is a good fit to the observed EGRB, and can account for the unexplained gamma-ray excess at $E \gtrsim 10\text{GeV}$. Moreover, we show that, even though the gamma-ray emission arising from structure formation shocks at galaxy clusters is below previous estimates, these large scale shocks can still give an important, and even dominant at high energies, contribution to the EGRB. Future detections of cluster gamma-ray emission would make our upper limit of the extragalactic gamma-ray emission from structure-formation process, a firm prediction, and give us deeper insight in evolution of these large scale shock.

Keywords: galaxy clusters – gamma rays, observations – gamma rays, theory – diffuse radiation

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1 INTRODUCTION

The extragalactic gamma-ray background was first detected via *SAS-2* satellite [1, 2], which was latter succeeded by the *EGRET* [3] and has most recently been measured by the *Fermi*-LAT [4] to the unprecedented precision. In the search for the origin of the EGRB multiple classes of sources were considered. Unresolved normal galaxies were found to be dominant contributors to the EGRB [5, 6]. Other sources like blazars [7–10] or dark matter annihilations [11], were also considered, but none of these, nor their combinations, managed to explain the entire background. *Fermi* observations revealed that the dominant emission mechanism is through cosmic-ray interaction with interstellar gas, which produces neutral pions π^0 which than decay into gamma rays $p_{\text{cr}} + p_{\text{ism}} \rightarrow \pi^0 \rightarrow \gamma + \gamma$ [12, 13]. This process, where cosmic rays are accelerated in supernova remnants, is responsible for the gamma-ray emission of observed star-forming galaxies [14–16] and contributes to the EGRB via unresolved normal galaxies. However, as cosmic rays are accelerated anywhere where shocks and magnetic fields are present, other cosmic-ray populations accelerated at different sites might also contribute to the observed EGRB. One such population are the cosmic rays accelerated during large scale structure formation (SFCRs) [17–19], however they are still hypothetical and yet to be observed. Good sites for observing potential gamma-ray emission from SFCRs are the nearby galaxy clusters [20–23], however only upper limits have been placed so far by *Fermi* [24]. Nonetheless, given that not much is known about this cosmic-ray population, nor their fluxes, nor their history, and that only very weak limits of their contribution to the EGRB have been placed so far [25–28], even a non detection of cluster emission can be used to make these limits much stronger. In this work we implement the semi-analytical source evolution of accretion shocks [16] and use cluster gamma-ray detection limits to build a model of the SFCR contribution to the EGRB.

2 FORMALISM

The differential gamma-ray intensity $dI_E/d\Omega$ [$\text{cm}^{-2}\text{s}^{-1}\text{GeV}^{-1}\text{sr}^{-1}$] is an observable quantity that describes the EGRB. Following Pavlidou & Fields (2002)[15] (hereafter PF02) and Prodanović & Fields (2004)[26] the differential gamma-ray intensity coming from SFCRs is

$$\frac{dI_E}{d\Omega} = \frac{c}{4\pi H_0} \int \frac{\dot{n}_{\gamma,\text{com}}[z, (1+z)E]}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}} dz, \quad (2.1)$$

where H_0 is the present value of the Hubble parameter and z is the redshift of the source. Matter and vacuum energy density parameters are given as Ω_m and Ω_Λ respectively. The differential co-moving gamma-ray emissivity density is $\dot{n}_{\gamma,\text{com}}$. In the case of gamma-ray emission from normal galaxies, where emission comes from cosmic rays accelerated in supernova remnants, $\dot{n}_{\gamma,\text{com}}$ is a function of the number density of galaxies and their individual emission. This can be related to cosmic star-formation rate $\dot{\rho}_*(z)$ as $\dot{n}_{\gamma,\text{com}} = L_\gamma n_{\text{gal}} \propto \dot{\rho}_*(z)$ (see equation 4 of PF02). In the case of SFCRs where the sources are large-scale structure formation shocks, their gamma-ray emissivity density $\dot{n}_{\gamma,\text{com}}$ can be expressed in terms of a similar quantity which we call the cosmic accretion rate $\dot{\rho}_{\text{sf}}(z)$ (co-moving mass current density crossing shock surfaces of any Mach number at a given cosmic epoch). Analytical models of cosmic accretion shocks were constructed by Pavlidou & Fields (2006)[29] (hereafter PF06) using the double distribution formalism of Pavlidou & Fields (2005)[30]. In their work, PF06 calculate the power and mass current that enters into these shocks of various strength and follow their evolution over redshift, taking into account the effect of the environment such as the preheating. Furthermore, PF06 demonstrate that their models are consistent with energetic of accreted mater that results from simulations. We will use the model of PF06 to implement the evolution of SFCR sources, for which we thus implicitly take only the cosmic accretion shocks. The gamma-ray emission resulting from a cosmic-ray population scales as a product of cosmic-ray flux and total mass of targets $L_\gamma \propto \phi_{\text{cr}} M_{\text{gas}}$. In the case of the galactic cosmic rays, their flux can be taken to be proportional to the star-formation rate, while similarly, in the case of cosmic rays originating from accretion shocks, the CR flux can be taken to be proportional to the mass accretion rate of a single shock $J(z)$. With that set, an average gamma-ray luminosity from structure formation can be determined as

$$L_\gamma(z, E) = \frac{J(z)}{J_0(z_0)} \frac{M_{\text{gas}}(z)}{M_{\text{gas}}(z_0)} L_{\gamma,0}(E), \quad (2.2)$$

where E is photon energy in the accretor rest frame and $M_{\text{gas}}(z)$ is gas mass contained in the accretor at a given cosmic epoch z , i.e. the mass of the intracluster gas. The rate at which mass crosses the surface of the single accretion shock at a given cluster is denoted $J(z)$. J_0 is the accretion rate of a cluster at z_0 to which we normalize, which should be taken as representative of the cosmic average. The gamma-ray luminosity of the normalization cluster is then $L_{\gamma,0}$. The implicit assumption in the above equation is that the ratio of accelerated to accreted particles is a constant. The emissivity density can thus be written as $\dot{n}_{\gamma,\text{com}}(z, E) = L_\gamma n_c$. Co-moving galaxy cluster number density n_c and cosmic accretion rate $\dot{\rho}_{\text{sf}}(z)$ are connected via $\dot{\rho}_{\text{sf}}(z) = J(z)n_c$. This gives the relation

$$\dot{n}_{\gamma,\text{com}}(z, E) = L_{\gamma,0}[(1+z)E] \frac{\dot{\rho}_{\text{sf}}(z)}{J_0(z_0)} \frac{M_{\text{gas}}(z)}{M_{\text{gas}}(z_0)}. \quad (2.3)$$

Assuming that on the onset of accretion when structure was virialized there was some initial gas mass $M_{\text{gas},0}$ defined with respect to the accreted gas as $M_{\text{gas},0} = \epsilon M_{\text{gas,acc}}(z_0)$, the above gas mass ratio can be written in terms of the accreted mass ratio as

$$\frac{M_{\text{gas}}(z)}{M_{\text{gas}}(z_0)} = \frac{\epsilon + M_{\text{gas,acc}}(z)/M_{\text{gas,acc}}(z_0)}{1 + \epsilon}, \quad (2.4)$$

where $M_{\text{gas,acc}}(z)$ and $M_{\text{gas,acc}}(z_0)$ are masses of gas accreted from the epoch of virialization up to the redshifts z and z_0 respectively. The ratio of the accreted masses is equal to the ratio of the cosmic accretion rates during those same epochs

$$\frac{M_{\text{gas,acc}}(z)}{M_{\text{gas,acc}}(z_0)} = \frac{\int_{z_{\text{vir}}}^z dz (dt/dz) \dot{\rho}_{\text{sf}}(z)}{\int_{z_{\text{vir}}}^{z_0} dz (dt/dz) \dot{\rho}_{\text{sf}}(z)}. \quad (2.5)$$

Finally, following PF02, equations (2.1), (2.2), (2.3), (2.4) and (2.5) combine to give the SFCR gamma-ray intensity as

$$\begin{aligned} \frac{dI_E}{d\Omega} = & \frac{c}{4\pi H_0 J_0(z_0)} \int_0^{z_{\text{vir}}} dz \frac{\dot{\rho}_{\text{sf}}(z) L_{\gamma,0} [(1+z)E]}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}} \\ & \times \left[\frac{\epsilon}{\epsilon + 1} + (\epsilon + 1)^{-1} \frac{\int_{z_{\text{vir}}}^z dz (dt/dz) \dot{\rho}_{\text{sf}}(z)}{\int_{z_{\text{vir}}}^{z_0} dz (dt/dz) \dot{\rho}_{\text{sf}}(z)} \right], \end{aligned} \quad (2.6)$$

where our solutions depends on the initial gas fraction parameter ϵ .

3 INPUTS

3.1 COSMIC ACCRETION RATE

For the total mass current density of gas entering into accretion shocks at a given epoch, which we call the cosmic accretion rate $\dot{\rho}_{\text{sf}}$, we use models constructed in PF06. The models present an analytical description of the energetics of the population of cosmic accretion shocks. We utilize their derived mass current distribution among different shock Mach numbers and their evolution with cosmic time, as a tracer of structure formation shock history, and thus a tracer of SFCR history. Three modes are separately analyzed in PF06, the simplest looks at all objects as being embedded in an environment well represented by the background universe. This model is based on Press-Schechter formalism, and will be labeled as Model 1, on our results. The second model of PF06 includes variations in the local matter density and temperature of the region around the accretor imprinted in the primordial density field, and will be labeled as Model 2. The third, most realistic model, also includes filament preheating and compression. This model will be labeled as Model 3 on our results. The latter two models that include environmental effects are based on a double distribution which describes how the number density of collapsed and virialized dark matter objects is distributed among different masses and among different local density contrasts with respect to the cosmic mean density [30].

Cosmic star formation rate is assumed to dictate the evolution of galactic cosmic-ray sources i.e. supernovae. In a similar manner we assume that the integrated mass current density derived from PF06 models dictates the evolution of SFCR sources i.e. it can be used to derive the cosmic accretion rate $\dot{\rho}_{\text{sf}}$.

3.2 GAMMA-RAY SPECTRA

For the shape of the pionic gamma-ray spectrum $\Gamma_{\gamma,\pi^0}(E)$ we used the semi-analytical formula derived by Pfrommer & Enßlin (2003)[31] as a representation of Dermer's model [32]. The spectrum in logarithmic space is symmetrical around half the pion rest mass m_{π^0} with the slope of the spectrum at high-energy end reflecting the spectral index α_γ of cosmic rays.

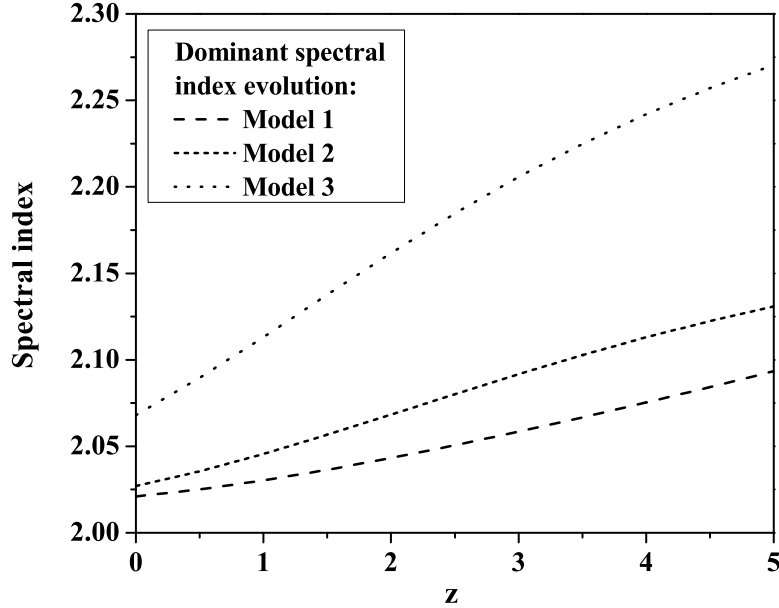


Figure 1: Evolution of dominant spectral index with redshift. The mean spectral index is derived from the mean Mach number which was for each epoch calculated from Mach number distribution of PF06 weighted over the cosmic accretion rate. Plotted curves were derived using models for evolution of cosmic accretion shocks (long dashed - Model 1, short dashed - Model 2, dotted line - Model 3) given in Pavlidou & Fields (2006)[29].

We have allowed for CR spectral index evolution according to the mean Mach number of cosmic accretion shocks at a given redshift. To determine the mean mach number at a given epoch we weight over the cosmic accretion rate distribution

$$\mathcal{M}_{\text{mean}} = \frac{\int (d\dot{\rho}_{\text{sf}}/d\ln \mathcal{M}) \mathcal{M} d\mathcal{M}}{\int (d\dot{\rho}_{\text{sf}}/d\ln \mathcal{M}) d\mathcal{M}}, \quad (3.1)$$

where the distribution over Mach numbers was taken from [16] (and private communication) for some discrete redshifts, which was then used to interpolate in order to determine the Mach number distribution and the mean Mach number for any other epoch. Also, the cosmic accretion rate $\dot{\rho}_{\text{sf}}$ that we use can be derived by integrating the cosmic accretion rate distribution over all shock Mach numbers. From the mean Mach number and corresponding spectral indices calculated over the range of redshifts, we find and implement in the overall gamma-ray spectrum originating from SFCRs. We note that in the redshift range 0 – 5 the spectral index varies between $\approx 2.05 - 2.30$ (Figure 1).

Even though large hopes were placed on *Fermi*-LAT when it comes to detection of galaxy clusters in gamma rays [33], no detections have been made yet. During the 18 months of *Fermi*-LAT observations, 33 clusters of galaxies were investigated and only upper limits have been reported [24]. Still, one can use the reported upper limits to set the normalization of the SFCR component of the EGRB, which itself is then the upper limit. We choose to normalize to the Coma cluster as a typical cluster, and thus use its *Fermi*-LAT upper limit,

as well as other corresponding parameters entering the equation (2.6) such as the Coma redshift $z_0 = 0.0232$ [34] and $z_{vir} = 1.5$ [35] for its virialization. To determine $L_{\gamma,0}$ we again assume a Pfrommer & Enßlin (2003)[31] gamma-ray spectral shape $\Gamma_{\gamma,\pi^0}(E)$, where for the spectral index we take $\alpha_\gamma = 2.01$ which was determined from the virial mass of Coma cluster $M_{200} = 2.65 \times 10^{15} M_\odot$ [36] (we use virial mass M_{200} as the total mass of Coma cluster M_{tot}) and the corresponding Mach number which would be suitable for accretion shocks developing on the Coma-type clusters. The virial mass M_{200} corresponds to a virial radius $r_{200} = 2.8 \text{ Mpc}$ [36] which is defined as the radius at which the interior mass density equals $200\rho_c$, where ρ_c is the critical density at the redshift of the cluster. For the gas mass M_{gas} of Coma cluster we use the value $M_{gas,500} = 19 \times 10^{13} M_\odot$ [34]. This corresponds to the radius r_{500} where the interior mass density equals $500\rho_c$. It is shown [37] that the gas mass fraction of the cluster depends on the cluster radius and the total mass. For clusters with masses similar to Coma cluster, the gas mass fraction remains fairly constant over the range or radii including r_{200} and r_{500} . With that set, and adopting the *Fermi* detection limit of Coma as actual detection with gamma-ray flux of $F_{\gamma,0} = 4.58 \times 10^{-9} \text{ phot cm}^{-2} \text{ s}^{-1}$ [24] integrated over the energy range $0.2 \text{ GeV} - 100 \text{ GeV}$, the normalization of the luminosity spectrum of Coma can be derived by requiring that $F_{\gamma,0} = \int dE L_{\gamma,0}(E)/4(1+z)d_c(z)^2\pi = C \int dE \Gamma_{\gamma,\pi^0}(E)/4(1+z)d_c(z)^2\pi$ where again $\Gamma_{\gamma,\pi^0}(E)$ is the shape of pionic spectrum, C is the spectrum normalization constant and $d_c(z) = 97 \text{ Mpc}$ is the co-moving distance of the cluster standardly defined as $d_c(z) = (c/H_0) \int_0^z dz'/\sqrt{\Omega_M(1+z')^3 + \Omega_\Lambda}$. Hence, the cluster luminosity is found to be $L_{\gamma,0}(E) = 5.28 \times 10^{45} \Gamma_{\gamma,\pi^0}(E) \text{ phot s}^{-1} \text{ GeV}^{-1}$.

4 RESULTS

The contribution of structure-formation cosmic-ray interaction to EGRB was derived from equation (2.6) based on the semi-analytical model of evolution of accretion shocks and the *Fermi*-LAT detection limit of the Coma cluster. The cosmological parameters used were $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$ and $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$. For our default case and results plotted on Figure 2 we adopt initial gas mass parameter $\epsilon = 0$. Our results are plotted on Figure 2 where we plot contributions of different components to the EGRB flux (data points) detected by *Fermi* [4]. Left pannel show each component separately, while right pannel sums over components and gives the total predicted EGRB. Solid lines represent contribution from star-forming galaxies in the two limiting cases of the model - luminosity evolution (top solid curve) and density evolution (bottom solid curve) [5]. Pure luminosity evolution is derived with redshift evolution of sources residing in galaxy luminosities, while their co-moving number density is constant. Pure density evolution is the case where evolution lies in co-moving number density of normal galaxies while their luminosity is constant. The dot-dashed line is the blazar contribution [38]. Contribution from structure-formation cosmic rays based on three different source models of PF06, and calibrated with Coma cluster detection limit, is presented with long dashed (Model 1), dashed (Model 2) and dotted curve (Model 3). Same line types relate to same models on the right pannel as well. Right pannel shows summed contribution from all components - blazars, star-forming galaxies and SFCRs. Red curves correspond to the luminosity, while blue curves correspond to the density evolution limiting case of the star-forming galaxy contribution to the EGRB as given in Fields, Pavlidou & Prodanović (2010)[5]. Our results show that the observed EGRB is best fitted with SFCR component where source evolution is based on the most simple model, Model 1 of PF06, while other models overshoot the observed data. Nevertheless, given that we have normalized our

models with Coma cluster observation limits, this shows that once the cluster(s) is detected, even if we were to normalize to a more modest cluster, rather than a rich cluster like Coma, SFCRs can still make an important and even dominant contribution to the EGRB.

On Figure 3 we demonstrate the sensitivity of our model with respect to the adopted initial gas mass content of a cluster represented by parameter ϵ . We see that for the two most extreme cases, our fiducial case $\epsilon = 0$ and limiting case $\epsilon = 10$ (note that for $\epsilon > 10$ the curves converge), the resulting curves differ by a factor of ~ 2 . To be as conservative as possible we thus keep $\epsilon = 0$ as our fiducial value.

5 DISCUSSION

We have constructed a model of the collective gamma-ray emission arising from the large scale accretion shocks around virialized structures, and estimated its contribution to the extragalactic gamma-ray background. Assuming that accretion shocks give rise to a new population of cosmic rays, the SFCRs, this would inevitably result in a gamma-ray flux which would contribute to the observed (but still unexplained!) EGRB at some level. Given that SFCRs are still a hypothetical population, with no direct observational evidence, and no known source evolution, so far only very weak upper limits have been placed to their contribution to the EGRB. In this work we have implemented source evolution based on the PF06 [16] model of cosmic accretion shocks around virialized structures, where we have also allowed for Mach number, and consequently cosmic-ray spectral index, evolution. To calibrate the resulting spectrum we have used gamma-ray flux upper limits reported by *Fermi* for galaxy clusters [24], specifically the Coma cluster.

Our results are presented on Figure 2. We see that the contribution of cosmic rays, arising from accretion shocks, to the observed EGRB can be dominant, especially at energies $> 10\text{GeV}$ compared to cosmic rays originating from star-forming galaxies. Moreover, depending on the assumptions, our discussed models go above the observed EGRB limits, allowing sufficient room for recalibration once clusters have been detected by gamma-ray observations, or for normalization fixed by a smaller cluster than Coma cluster adopted in this work. Thus a positive cluster detection would not only make our upper limit model of SFCR contribution to the EGRB into a prediction, but would also serve, within our model, as a probe of the SFCR source evolution. For the specific case of the Coma cluster, such detection might be within reach, given that new predictions [39], which are at the same time successful in explaining the Coma cluster radio halo, fall just below the present *Fermi* limits. Recently, Keshet et al. (2012) [40] have reported a detection with VERITAS Cherenkov array of the gamma-ray ring around the Coma cluster. The reported signal is claimed to be synchrotron and Inverse Compton emission from relativistic electrons accelerated in large-scale shocks. Since the hadronic gamma-ray emission is thought to be subdominant in the reported signal, we cannot directly use this to calibrate our model, however, if confirmed, such detection would be important for constraining the population of structure-formation cosmic rays around clusters.

In terms of the uncertainty, our model is slightly sensitive to the choice of the virialization redshift of the accretor. Normalizing to a galaxy cluster with a larger virialization redshift would result in a slightly higher collective gamma-ray emission and contribution to the EGRB. However, the mean Mach number at a given redshift, and the mean spectral index, do not change much in the sense that we are always dealing with close-to-strong shocks. On the other hand, the choice of a model for the cosmic accretion rate $\dot{\rho}_{\text{sf}}$ from PF06 can

change the results by about one order of magnitude. Using the simplest model (Model 1) presented in PF06, which was based only on the Press-Schechter distribution, where all objects accrete baryons of the uniform density and temperature, the resulting spectrum is lower than in the case of a more realistic model with density and temperature variations around accretor. Even though it involves the most simplistic assumptions, we find that our model based on the source evolution of Model 1, results in the SFCR gamma-ray component that fits the observed EGRB best. Our model also depends on the choice of the galaxy cluster to which we normalize. Cluster size, distance, mass and especially the adopted flux upper limit can change the resulting spectrum up to two orders of magnitude. We have chosen Coma cluster as a good candidate for normalization since it is a rich cluster, but with intermediate values for cluster size, mass and flux upper limit. Since no clusters were actually detected, the largest uncertainty of our model comes from flux upper limits. In a recent work by Zandanel *et al.* (2012)[41] gamma-ray fluxes from galaxy clusters were estimated and their models show these fluxes to be up to 2 orders of magnitude below the *Fermi* limit for some of the clusters.

Our new constraint on the SFCR contribution to the EGRB, has multiple implications. For instance, a concern was raised that SFCRs could potentially produce important quantities of lithium isotopes which would increase the severity of the lithium problem [42, 43]. Since we have shown that SFCR contribution to the EGRB can be important, corresponding lithium production [44] could also be relevant. Similarly, neutrino fluxes accompanying this cosmic-ray population could also make an important contribution to the neutrino background arising from other sources like dark matter annihilations [23, 45].

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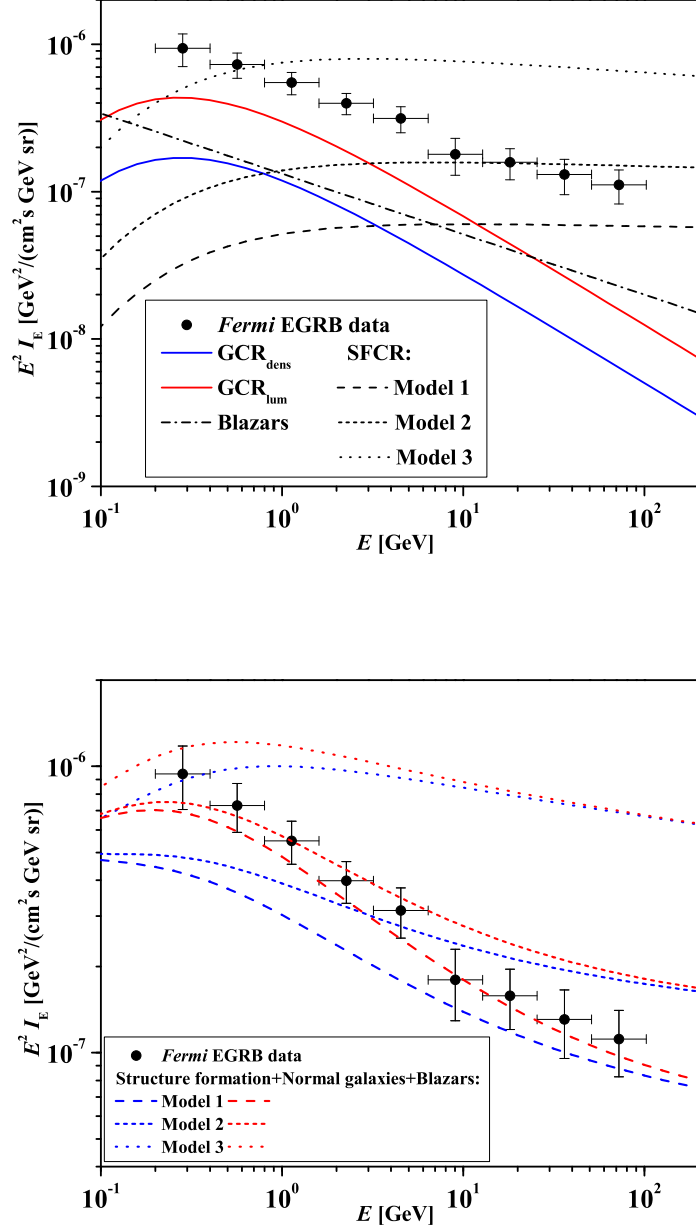


Figure 2: Contribution of different components (normal galaxies, blazars, structure-formation cosmic-rays) to the EGRB (data points) observed by *Fermi* [4]. *Top panel:* All components shown separately - blazars (dot-dashed line), normal star-forming galaxies based on two limiting cases given in Fields, Pavlidou and Prodanović (2010)[5] (solid red line - luminosity evolution, solid blue line - density evolution), and SFCR contribution calculated in this work, normalized to the Coma cluster gamma-ray flux limit and based on the three different source models derived in Pavlidou & Fields (2006)[29] (long dashed - Model 1, short dashed - Model 2, dotted line - Model 3). *Bottom panel:* The combined contribution of blazars, normal galaxies (red curves - luminosity evolution, blue curves - density evolution) and gamma radiation origination from SFCRs as calculated in this work (three different line types correspond to the same models as on the top panel). All SFCR curves were calculated adopting the initial gas mass parameter $\epsilon = 0$.

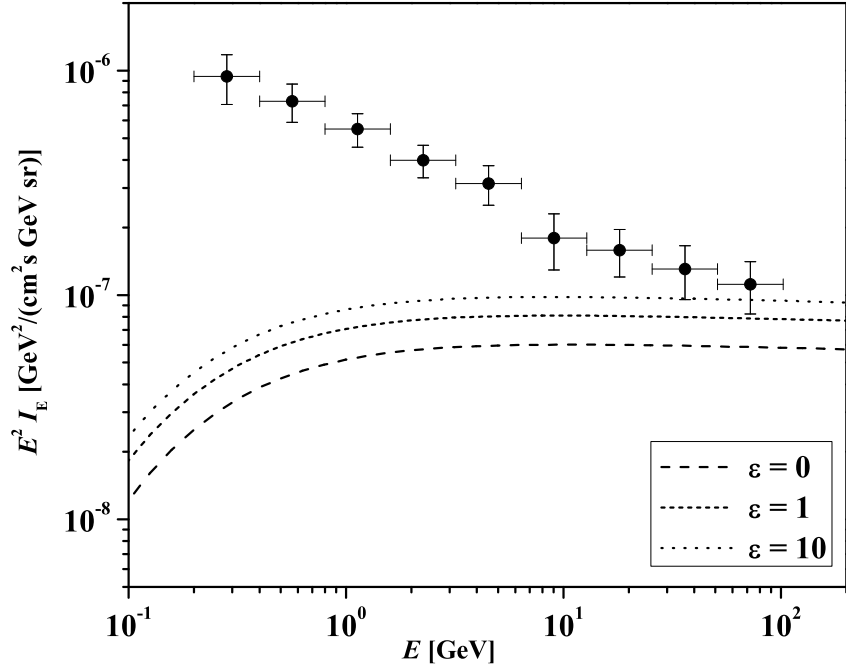


Figure 3: This plot shows the sensitivity of our model on the adopted initial gas mass fraction parameter ϵ . For the purpose of demonstration we plot the SFCR gamma-ray curve based on Model 1 of PF06, and derived adopting different initial gas mass fraction values $\epsilon = 0, 1, 10$. The top most curve is approximately factor of 2 higher than our fiducial case plotted on Figure 2. For all $\epsilon > 10$ all curves converge and are overlapping with the $\epsilon = 10$ curve.